

3.0 SEC Mission Roadmap Introduction

Sun-Earth Connection (SEC) missions traditionally fall into one or more of four broad disciplines: solar, heliospheric, magnetospheric (including comparative magnetospheres), and Ionospheric/Thermospheric/Mesospheric (ITM), representing each of the major disciplines in the Division. Missions within the Sun-Earth Connection Division can also be categorized by different measurement techniques. Solar missions sense the Sun remotely via imaging and spectroscopy over a variety of scale lengths and wavelengths. Heliospheric and magnetospheric missions generally return *in situ* measurements of particles, fields, and plasmas. ITM missions use both remote sensing (e.g., auroral imaging) and *in situ* measurements to determine atmospheric and ionospheric parameters.

Achieving SEC science objectives will necessitate changes in the conduct of new missions. Understanding the Sun, heliosphere, and planetary magnetospheres, ionospheres, and atmospheres as a single coupled system requires a melding of SEC missions and correspondingly distinct changes in measurement techniques. Because of this requirement, there is an evolution from single-point or widely spaced multi-point SEC missions employing only one or a few measurement techniques to coupled, multi-point missions that employ a variety of measurement techniques.

Solar physics has traditionally relied on remote sensing. Because of the inherent difficulty in performing *in situ* observations very near the Sun, new missions in the SEC continue to rely on these measurements. However, addressing key science questions also requires some important changes in the way these missions are designed. Two significant changes in new solar missions will be a dramatic increase in accumulated data (to accommodate the necessary increases in temporal and spatial resolution) and important changes in the observation vantage points. The dramatic increase in data will require new analysis and modeling techniques. Many new missions will not be confined to vantage points near the Earth. For example, they will image active regions from heliosynchronous orbits, keeping the same perspective of the active region under investigation. In addition, multi-spacecraft missions will provide continuous imaging of the entire solar surface. One of the most significant changes in solar physics will be the strengthening of ties

between the solar and heliospheric communities. Inner heliospheric missions will use a combination of solar imaging and *in situ* measurements to directly link activity on the Sun with consequences in the heliosphere. Further, the region between a few solar radii and 0.3 AU (>60 solar radii) will be explored for the first time using *in situ* measurements supported by imaging to resolve critical science questions.

Heliospheric physics will undergo a similar revolution. Study of the inner heliosphere will benefit from the first heliospheric mission specifically designed to provide multi-point measurements. Study of the heliosphere at high latitudes will build upon the results obtained from Ulysses by combining *in situ* measurements with imaging of the Sun's polar regions. New SEC missions will combine multi-point, remote sensing of CMEs with multi-point *in situ* measurements of the particles accelerated in these structures. This combination will reveal how CMEs change as they propagate away from the Sun and will link these changes with the origin of the structure in the solar atmosphere. Global imaging of the outer heliosphere will be followed by new missions providing *in situ* measurements of the previously unexplored inner and outer boundaries of the heliosphere.

Recent multi-point and global imaging missions signal the path to advance magnetospheric physics. These missions demonstrate the need to distinguish spatial from temporal phenomena via multi-point measurements throughout the magnetosphere. The new magnetospheric missions will employ focused multi-point measurements, global imaging, or both these techniques to answer key science questions. Magnetospheric physics will also benefit significantly from comparison with the results from missions to other planets with similar magnetospheric and ionospheric processes.

ITM missions have traditionally benefited from a combination of imaging and *in situ* measurements. New missions will also use these techniques, but like their magnetospheric counterparts, they will employ multi-point measurements to distinguish spatial from temporal phenomena. ITM missions, like solar missions, will continue to benefit from ground-based observations. These observations provide critical contextual measurements of regions surrounding a low Earth orbiting spacecraft. Finally, although there has always been a strong link between atmospheric, ionospheric, and magneto-

spheric physics, new missions will be specifically targeted to operate in concert in all regions to answer important questions concerning the coupling among the regions.

Of all the changes, the most important is the emphasis on the Sun, Earth, and heliosphere as a single, highly coupled system. Thus, while the individual missions that are described below address directly the objectives of the SEC Division, many

of these objectives are attained best by operating missions in concert with one another. Furthermore, theory and modeling play an important role in interpreting the observations from near- and intermediate-term multi-spacecraft missions and driving the development of future long-term missions. Our specific technology needs are discussed in Section 4.

Table 3.1.1: Near-, intermediate-, and long-term missions for understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Near-Term Missions (2003 – 2008)	Intermediate-Term Missions (2009-2014)
<p>Solar B</p> <ul style="list-style-type: none"> - How is the photosphere magnetically coupled to the corona? <p>Solar-TERrestrial RELations Observatory (STEREO)</p> <ul style="list-style-type: none"> - What are the origins and consequences of CMEs? - What processes control CME dynamics and evolution? - How and where are energetic particles accelerated in CMEs? <p>Geospace Electrodynamic Connections (GEC)</p> <ul style="list-style-type: none"> - How does the Earth's ionosphere-thermosphere (I-T) system respond to magnetospheric forcing? - How is the I-T system coupled to the magnetosphere? <p>Solar Probe</p> <ul style="list-style-type: none"> - What are the origins of the fast and slow solar wind? - Why is the Sun's corona hot? 	<p>Magnetospheric Constellation (MC)</p> <ul style="list-style-type: none"> - How does the magnetotail control energy flow in the magnetosphere? - What processes control magnetotail structure and dynamics? - How do physical processes and regions of the magnetosphere couple over the hierarchy of scales? <p>Telemachus</p> <ul style="list-style-type: none"> - What is the large scale, 3-dimensional structure of the heliosphere? - How is the heliosphere reconfigured over the course of single and multiple solar cycles? <p>Ionosphere Thermosphere Mesosphere (ITM) Waves Coupler</p> <ul style="list-style-type: none"> - What are the global characteristics, variability, and sources of small-scale waves in the Earth's upper atmosphere? - What are the consequences of wave-induced transport between the upper and lower atmosphere? <p>Heliospheric Imager and Galactic Observer (HIGO)</p> <ul style="list-style-type: none"> - What is the nature, size, and variability of the heliospheric boundaries? - What is the composition of interstellar gas?
Long-Term Missions (2015 – 2028)	
<p>Auroral Multiscale (AMS)</p> <ul style="list-style-type: none"> - How is the Earth's high latitude ionosphere electrostatically coupled to the magnetosphere? <p>Geospace System Response Imager (GSRI)</p> <ul style="list-style-type: none"> - How is mass and energy transported between the ionosphere and magnetosphere under both quiescent and active conditions? <p>Interstellar Probe</p> <ul style="list-style-type: none"> - What is the nature of the interstellar dust and gas that interacts with the solar system? - How is the elemental composition of the interstellar medium distributed between solid (dust), neutral (gas), and plasma (ionized gas) states? <p>Neptune Orbiter</p> <ul style="list-style-type: none"> - What are the structure and solar wind interactions of a planetary magnetosphere whose spin axis and magnetic dipole axis are in very different directions? <p>SCOPE</p> <ul style="list-style-type: none"> - How are processes in the magnetospheres and upper atmospheres of the planets similar to those observed at Earth? <p>Solar Polar Imager</p> <ul style="list-style-type: none"> - How do active regions on the Sun form and evolve at high latitudes? - What is the nature of the velocity vector field below the surface of the poles of the Sun? 	

Table 3.1.2 Investigations for understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments and their relationships to near-, and intermediate-term missions.

Investigation	Near-Term Missions				Intermediate-Term Missions			
	Solar B	STEREO	GEC	Solar Probe	MC	Telemachus	ITM Waves Coupler	HIGO
(a) Understand the transport of mass, energy, and magnetic fields within the Sun and into the solar atmosphere	P	S		S				
(b) Determine through direct and indirect measurements the origins of the solar wind, its magnetic field, and energetic particles		P		P		S		
(c) Determine the evolution of the heliosphere on its largest scales		S		S		P		S
(d) Determine the interaction between the Sun and the galaxy						S		P
(e) Differentiate among the dynamic magnetospheric responses to steady and non-steady drivers			S		P			
(f) Explore the chain of action/reaction processes that regulate solar energy transfer into and through the coupled magnetosphere-ionosphere-atmosphere system			P				P	

P = Primary science investigation for the mission

S = Secondary science investigation for the mission

3.1 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments depends critically on an understanding of the strong and complex linkages between regions. Consequently, this science objective requires a linked set of missions to systematically establish the flows from their source (or sources), through the regions where they evolve, to their ultimate destinations. The SEC Division has a set of near-, intermediate-, and long-term missions (discussed below) that systematically and deliberately focus on each of the key regions, the most important and relevant processes occurring in these regions, and the ways by which these regions and processes are linked. While the missions described below are each stand-alone and significant, by virtue of the story that they tell together, their collective value is greater than the sum of their parts.

3.1.1 Near-Term Missions

Solar B

Solar B will characterize the magnetic coupling between the Sun's photosphere and corona through

high temporal and spatial resolution imaging of active regions. It is a single spacecraft mission in Sun-synchronous orbit around the Earth. The mission is a joint undertaking of the Japanese Institute of Space and Astronautical Science (ISAS), NASA, and the UK that is being led by and launched by Japan. The objectives of Solar B are to analyze creation and destruction of the Sun's magnetic field, luminosity modulation, X- and UV-radiation variation, and eruptions in the Sun's atmosphere. The instrument complement includes a visible light spectrograph and vector magnetograph, an X-ray telescope, and an imaging UV spectrograph. The fields of view of the imagers will cover an active region including full vector magnetic field measurements with a resolution a factor of 10 better than currently available.

Solar-TERrestrial RELations Observatory (STEREO)

STEREO will describe the 3-D structure and evolution of coronal mass ejections (CMEs) from their eruption on the Sun through the inner heliosphere to Earth's orbit. The mission will employ remote sensing and *in situ* measurements from two spacecraft drifting in opposite directions away from the Earth at 1 AU to triangulate CME-driven

shocks, detect preceding shock-accelerated particles, and analyze *in situ* CME and solar ejecta signatures, including heavy ion mass and charge states. The instrumentation package on each spacecraft includes a coronal and heliospheric imaging package (with an EUV imager, two coronagraphs, and heliospheric imager), a set of radio wave receivers, and an array of *in situ* measurements for measuring the solar wind, energetic particles, and interplanetary magnetic fields.

Geospace Electrodynamic Connections (GEC)

GEC will define the dynamic nature of the joint ionospheric and thermospheric response to magnetospheric forcing. This multi-spacecraft mission will focus on the hitherto relatively unexplored lower reaches of the ionosphere and thermosphere from 100 to 150 km, where the neutral atmosphere plays a preeminent role in processing and dissipating the electromagnetic energy received from the magnetosphere. GEC will discover the spatial and temporal scales at which magnetospheric energy input is important, determine the scales for the response of the IT system to this input of energy, and quantify the altitude dependence of the response. The GEC spacecraft will be identically instrumented to sample *in situ* the ionized and neutral gases of the upper atmosphere and to measure the electric and magnetic fields that couple the IT system to the magnetosphere. They will use onboard propulsion to plunge repeatedly to altitudes below the nominal 185 km perigee. During these low-perigee excursions and at other times, GEC and ground-based measurements will be coordinated to provide both global and local perspectives.

Solar Probe

Solar Probe will enter the solar atmosphere to identify the source regions for the solar wind, determine the mechanisms leading to the solar wind and other stellar winds, and trace the flow of energy from the corona into the solar wind. The distribution functions of particles, the properties of waves, the structure of boundaries and discontinuities, the energetic particles, and the elemental composition will be measured at spatial resolutions of ~100 km or less. These will be compared with photospheric and magnetogram images with similar resolution to determine the mechanisms that accelerate the solar wind and produce energetic particles.

3.1.2 Intermediate-Term Missions

Magnetospheric Constellation (MC)

MC will employ a constellation of ~50 spacecraft to describe the temporal and spatial structure of complex processes occurring throughout vast regions of the Earth's magnetosphere. *In situ* plasma, magnetic field, and energetic particle observations, and possibly imaging, will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The data will be provided on spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing where magnetic flux, mass transport, energy conversion, and dissipation occur. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

Telemachus

Telemachus will define the large scale, 3-D structure of the source region for most of the solar wind and magnetic field in the heliosphere. At 0.2 AU perihelion, Telemachus will determine the physics of the strongest stream/stream plasma interactions and transient shocks in the inner heliospheric region where they first form. On each ~0.4 AU polar pass, it will observe the high-latitude distribution of radio and x-ray emission from all solar longitudes simultaneously and use helioseismology to study the coupling of convection and rotation and the accumulation of magnetic flux in the polar regions. During the remainder of its orbit, the out-of-ecliptic vantage point of this mission will be used to understand the evolution of the solar wind transition to the outer heliosphere and determine the 3-D structure of the heliosphere with time.

Ionosphere-Thermosphere-Mesosphere Waves Coupler

The ITM Waves Coupler will determine the characteristics and effects of gravity waves in the upper atmosphere on a global scale. The ITM Waves Coupler mission will define the global characteristics, variability, and sources of small-scale

gravity waves originating in the lower atmosphere and their influence on mesospheric, lower thermospheric, and ionospheric circulation. The mission will also quantify the effects of the circulation, composition, and transport between the thermosphere and lower atmosphere on the water budget, on the influences of polar mesospheric clouds, and the distribution of chemically-active constituents of the upper atmosphere. These objectives will be accomplished by integrating *in situ* and remote-sensing measurements from two spacecraft on low- and high-apogee orbits with state-of-the-art modeling tools. The imagers on both spacecraft will observe the elusive small-scale waves that determine energy input into the upper atmosphere. On the high inclination spacecraft, infrared spectroscopy will determine transport associated with the waves by measuring chemical composition.

Heliospheric Imager and Galactic Observer (HIGO)

HIGO is the first step into the interstellar medium. It is a single spacecraft in an eccentric orbit around the Sun with 1 AU perihelion and >4 AU aphelion. The mission will determine the 3-D structure and temporal evolution of the interaction region between the heliosphere and the local galactic environment, determine the nucleosynthetic status of a present-day sample of the galaxy. It explores the implications of this environment for Big Bang cosmology, galactic evolution, stellar nucleosynthesis, and the birthplace of the Sun. It searches for molecules and the building blocks of life from pickup molecules (generated through sputtering or sublimation, ionization, and subsequent pickup by the solar wind) left by comets and dust in the heliosphere and interstellar medium. Beyond 4 AU, the heliospheric boundaries may be imaged using Energetic Neutral Atoms (ENAs) and EUV emissions. Instruments will sample pickup ions produced from the neutral galactic matter, thereby determining isotopic and elemental composition of the Local Interstellar Medium and other heliospheric sources. The major neutral components of the interstellar gas will be directly sampled to provide more accurate measurements of the temperature and bulk flow velocity of the local interstellar gas. These measurements will be an important precursor to the follow-on mission that will directly sample the interstellar medium outside the termination shock.

3.1.3 Long-Term Missions

Auroral Multiscale (AMS)

AMS will define the electrodynamic connection between the Earth's auroral ionosphere and the magnetosphere. It utilizes four or more spacecraft that fly in formation through the auroral acceleration region at varying altitudes between 600 and 7000 km. Spacecraft separations vary between ~1 km to 1000 km. Each spacecraft samples the physical processes occurring within the auroral acceleration region (plasma, DC and AC magnetic and electric fields) with time resolution appropriate for the phenomena (from seconds to tens of milliseconds). The spacecraft also obtain high-resolution ultraviolet images of the consequences of those processes within the aurora at the magnetic footpoints of the spacecraft cluster. The combination of four spacecraft provides the unique ability to separate spatial and temporal effects and to measure the magnetic field-aligned electric current for varying conditions.

Geospace System Response Imager (GSRI)

GSRI characterizes the global-scale coupling throughout geospace. It is a combined high and low altitude, multi-spacecraft mission, leveraging innovative imaging capabilities. The high altitude component of GSRI, is composed of two identically instrumented nadir-viewing spacecraft in identical circular polar orbits. These will provide nearly continuous stereoscopic ENA and EUV imaging of the magnetosphere, determining the hot plasma morphology and energy content and global electric field distribution. Auroral and airglow imaging instruments on the high-altitude spacecraft will provide nearly continuous and conjugate remote observation of the ionosphere and thermosphere, allowing measurement of the distributions of precipitating electron energy flux, ionospheric electron density, and thermospheric neutral density, composition and temperature. The important components missing from the high altitude measurements will be obtained using GSRI's low altitude component, which consists of two minimally instrumented spacecraft in identical circular low Earth orbits. These spacecraft do regional conjugate imaging of ionospheric plasma convection and neutral wind patterns, augmented with ground-based observations. They provide global specification of the ionospheric electric field and electric current patterns in both hemispheres, essentially completing the electrodynamic picture at low altitude and matching this picture to

the one imaged at high altitudes. This mission will also investigate the little-understood role of inter-hemispheric asymmetry (due to the tilt of the dipole and rotation axes) on the global system behavior.

Interstellar Probe

Interstellar Probe is the first mission outside of the Sun's heliosphere. It is a single spacecraft that will use an advanced in-space propulsion system such as a solar sail or nuclear electric propulsion to reach the upstream interstellar medium at a distance of 200 AU within about 15 years. This spacecraft will carry the first payload specifically designed to determine the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the thick interaction region between the heliosphere and the interstellar medium extending from the termination shock to the heliopause. Eventually, Interstellar Probe may cross an external bow shock, should that shock exist. Additional advanced instrumentation will determine the nature and chemical evolution of organic molecules in the outer solar system and interstellar medium and perhaps expose the cosmic infrared background (CIRB) radiation normally hidden by the Zodiacal dust.

Neptune Orbiter

Neptune Orbiter will determine the characteristics of a magnetosphere that is considerably different from the Earth's magnetosphere. It is a single spacecraft mission in a moderate inclination, eccentric orbit around Neptune. From this vantage point, it will determine the nature of the Neptune magnetosphere, which is unique in the solar system because its magnetic dipole tilt varies dramatically over Neptune's 16-hour spin period and is significantly different from its rotation axis. The *in situ* plasma and magnetic field measurements will determine the interaction of this unusual magnetosphere with the solar wind and will determine if Triton has an intrinsic magnetic field and interacts with the magnetosphere.

Solar Connections Observatory for Planetary Environments (SCOPE)

SCOPE explores the range of planetary magnetospheres and upper atmospheres of the planets. It is a set of Hubble Space Telescope-class, state-of-the-art remote sensing telescopes to carry out a

broad program in comparative magnetosphere and upper atmospheres, producing a global-systems view of the response of planetary environments to the variations in the solar wind, the Sun's ultraviolet radiation, and internal processes. When SCOPE telescopes are pointed back toward Earth, advanced detector capabilities and precision filters, designed for the challenge of planetary auroral and airglow observations, provide an exciting advance in the spatial and spectral resolution of global auroral images and make the first-time ever global observations of the energy and flux of precipitating oxygen ions, a tracer of the coupling between the Earth's upper atmosphere and magnetosphere. SCOPE will map, monitor, and compare terrestrial and other planet auroral mass and energy deposition patterns, magnetospheric plasma processes, coronal emissions, and upper atmospheric structure and circulation, with proven techniques of wide and narrow field of view (FOV) spectro-imaging and line profile measurement.

Solar Polar Imager

Solar Polar Imager will define a critical missing component in the understanding of the solar cycle. It is a single spacecraft mission that uses solar sails to achieve a final 0.48 AU circular orbit with a 60° inclination to the ecliptic. This orbit is in 3:1 resonance with Earth. The spacecraft carries a Doppler imager for high-resolution helioseismology measurements, a solar magnetic field imager, *in situ* particles and fields instrumentation and a solar irradiance monitor. The 3:1 resonance permits this mission to also carry out the helioseismology measurements on the far side of the Sun from the Earth. This combined imaging and *in situ* instrument suite will make high-resolution helioseismology measurements of the Sun's polar regions down to the equator, tracing the complete life cycle of active regions and coronal holes on the Sun and placing far greater constraints on the deep structure of the Sun.

3.2 Explore the fundamental physical processes of space plasma systems.

A plasma is governed by fundamental physical properties related to its ability to support electric and magnetic fields. Among these properties, there are three that are important for understanding Sun-heliosphere-planet connections and, not by coincidence, are part of other astrophysical phenomena.

These are: creation, annihilation, and reconnection of magnetic fields, acceleration of charged particles, and cross-scale coupling. Missions within the SEC Division investigate these fundamental properties and determine their physical origin as well as their

generality in other places in the universe. These missions are listed in Table 3.2.1.

Table 3.2.1 Near-, intermediate-, and long-term missions that explore fundamental properties of plasmas.

Near-Term Missions (2003 – 2008)		Intermediate-Term Missions (2009-2014)	
Magnetospheric Multiscale (MMS) <ul style="list-style-type: none">- Why do magnetic fields reconnect?- What is the nature of turbulence in geospace?- How are magnetospheric particles accelerated? Bepi-Colombo <ul style="list-style-type: none">-How do planetary magnetic fields interact with the solar wind in the absence of an ionosphere?		Jupiter Polar Orbiter (JPO) <ul style="list-style-type: none">- How similar and different are fundamental auroral acceleration processes at Jupiter and Earth?- How does auroral coupling moderate the transfer of momentum by magnetic fields in astrophysical systems? Reconnection and Microscale (RAM) <ul style="list-style-type: none">- What mechanisms lead to reconnection in the solar corona?- Where are regions of particle acceleration?- What micro-scale instabilities lead to global effects?	
Long-Term Missions (2015 – 2028)			
Dayside Boundary Layer Constellation (DBC) <ul style="list-style-type: none">- What is the global magnetic field topology of the Earth's dayside magnetopause?- How does turbulence in the magnetosheath or at the magnetopause modify plasma transfer across the magnetopause boundary? Io Electrodynamics <ul style="list-style-type: none">- What are the energy coupling processes operating in a magnetosphere with an active moon? Magnetosphere-Ionosphere Observatory (MIO) <ul style="list-style-type: none">- How is energy tapped from the Earth's magnetosphere to power auroral arcs in the high-latitude ionosphere? Mars Aeronomy <ul style="list-style-type: none">- How is the upper atmosphere of Mars electromagnetically coupled to the solar wind? Particle Acceleration Solar Orbiter (PASO) <ul style="list-style-type: none">- How are the most energetic particles accelerated and transported in and around the Sun? Venus Aeronomy <ul style="list-style-type: none">- What are the electrodynamic interactions of the solar wind with a planet without an intrinsic magnetic field?			

Table 3.2.2 Investigations for exploring the fundamental physical processes of space plasma systems and their relation to near- and intermediate-term missions.

Investigation	Near-Term Missions		Intermediate-Term Missions	
	MMS	Bepi-Colombo	JPO	RAM
(a) Discover the mechanisms for creation, annihilation, and reconnection of magnetic fields	P			P
(b) Determine how charged particles are accelerated to enormous energies	S		S	S
(c) Understand how small scale processes couple to large-scale dynamics	S	S	S	S
(d) Test the generality of processes in diverse plasma environments		P	P	

P = Primary science investigation for the mission

S = Secondary science investigation for the mission

3.2.1 Near-Term Missions

Magnetospheric Multiscale (MMS)

MMS will determine the fundamental physical properties of magnetic reconnection. It is a four spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence (cross-scale coupling) in key boundary regions of the Earth's magnetosphere. The primary goal of the mission is to use high time resolution, *in situ* plasma and fields measurements to determine the micro-scale processes in the exceedingly small (perhaps <100 km thick) diffusion region, where the electrons in a plasma become decoupled from the magnetic field, and the field reconnects. This region is found at the Earth's magnetopause and in the magnetotail, but has never been visited by spacecraft with proper *in situ* instrumentation. The close spacecraft spacing will also enable exploration of the cross-scale coupling of plasma turbulence in the Earth's magnetosheath, at the magnetopause, and in the magnetotail. Finally, charged particle acceleration processes associated with magnetic reconnection, turbulence, and electric fields in the outer magnetosphere will be determined using direct measure of the plasma and waves that cause the acceleration.

Bepi-Colombo

Bepi-Colombo will explore Mercury and its interaction with the solar wind. It is a two-spacecraft ESA mission done in cooperation with Japan. The instruments on the Bepi-Colombo Mercury Planetary Orbiter (MPO) will consist of cameras and spectrometers for high-resolution imaging and spectroscopy of the surface, including emissions from the surface and energetic neutral atoms produced by solar wind-surface interactions. The Mercury Magnetospheric Orbiter (MMO) will carry detectors to observe Mercury's magnetic field and its interactions with the solar wind. Despite significant differences between the atmospheres, magnetic fields, and magnetospheres of Mercury and the Earth, there is evidence that Mercury undergoes a sub-storm-like solar wind interaction. Magnetic field, wave and particle measurements from MMO will determine the similarities and differences between the magnetospheric processes at Mercury and Earth.

3.2.2 Intermediate-Term Missions

Reconnection and Microscale (RAM)

RAM will reveal the mechanisms leading to reconnection in the solar corona. It is a single spacecraft, Earth orbiting mission that uses a suite of narrow-band and spectroscopic imaging telescopes to take very high resolution images of the solar atmosphere and corona. It improves the resolution of solar atmosphere and corona imaging by a factor of more than 1000 over current measurements. These high resolution measurements will be used to determine the topology of reconnection regions on the Sun, infer the mechanisms that lead up to reconnection and the micro-scale instabilities that lead to global effects, and determine the regions of particle acceleration. The mission takes advantage of geosynchronous orbit for nearly continuous monitoring of the Sun and a large bandwidth downlink for the high spatial and temporal resolution data. To image the small-scales of reconnection and the large-scale consequences of the process, RAM combines extremely high spatial resolution in the corona (~10 km) with intermediate scale (~70 km) large field-of-view observations at several complementary passbands/temperatures. The spectroscopic instruments are a high resolution (~70 km spatial, ~5 km/s velocity) imaging EUV spectroscopy and a photon counting (~700 km, ~10 km/s velocity, ~50 ms time) imaging X-ray micro-calorimeter array.



Figure 3.1 (Left side) An arc structure on the Sun undergoing reconnection (Right side) shows the Earth's magnetosphere on the same scale as the arc structure. MMS will determine the micro-scale processes responsible for reconnection in the Earth's magnetotail through high time resolution *in situ* measurements. RAM will determine the global topology and infer the micro-scale processes of reconnection using images of the solar atmosphere and corona with resolution more than 1000 times better than shown here.

Jupiter Polar Orbiter (JPO)

JPO will develop a unique understanding of the electromagnetic connection between the planet's magnetosphere and ionosphere. It is a single spacecraft in polar orbit around Jupiter. Through comparison with results from previous Earth-orbiting missions, JPO will distinguish those aspects of the field-aligned coupling phenomena that are characteristic of astrophysical plasmas in general and those that are unique to the special conditions that prevail at each planet. With its polar orbit, the JPO spacecraft flies repeatedly through the northern and southern hemisphere auroral acceleration regions, similar to what spacecraft have done at Earth. JPO measures *in situ* magnetic fields (inferring field-aligned currents), plasmas, energetic particles, and waves and images the aurora in UV. Radio occultations are used to probe the ionosphere and the thermosphere. JPO will achieve at Jupiter what other spacecraft have achieved at Earth: the most complete characterization of the auroral and magnetosphere-ionosphere coupling possible from a single spacecraft. Planetary science objectives will be included with additional instrumentation, specifically those instruments needed to probe the internal structure of Jupiter, the magnetic dynamo of Jupiter, and atmospheric dynamics.

3.2.3 Long-Term Missions

Dayside Boundary Layer Constellation (DBC)

DBC will determine the global topology of magnetic reconnection at the magnetopause. It is a network of ~ 30 Sun-pointing, spinning, small spacecraft, separated by $\sim 1 R_E$, that skim both the dawn and dusk sides of the dayside magnetopause. The multi-spacecraft provide simultaneous comprehensive observations of boundary phenomena including turbulence over a wide range of latitudes and local times. Three spacecraft are boosted to have apogee outside the bow shock to provide continuous monitoring of the foreshock-preconditioned solar wind input. In effect, DBC spacecraft image the variable geometry of magnetic reconnection much the same way that high-resolution images of the Sun (e.g., from the RAM mission) reveal the location and topology of reconnection and particle acceleration.

Io Electrodynamics

Io Electrodynamics will determine the coupling of an active moon to its planetary magnetosphere. It is a single spacecraft mission in eccentric equatorial orbit around Jupiter. It makes repeated flybys of Io in order to determine how this active moon couples to the Jovian magnetosphere. The spacecraft measures the particles and electric and magnetic fields necessary to determine the field-aligned currents that couple Io and its torus to the Jovian ionosphere. An understanding of this process enhances the understanding of the magnetosphere-ionosphere coupling at the Earth and serves as a bridge to understanding of other multiple component astrophysical systems.

Magnetosphere-Ionosphere Observatory (MIO)

MIO will determine the processes that drive auroral arcs. It is a tight cluster of satellites in geosynchronous orbit that are magnetically connected to a ground-based observatory, with a satellite-based electron beam establishing the precise connection to the ionosphere. One of the longest standing problems in magnetosphere-ionosphere coupling is the fundamental question how large-scale processes in the magnetosphere (with spatial scales of many thousands of kilometers) effectively couple to the ionosphere to produce very narrow auroral arcs (with scales less than 1 km). The MIO spacecraft cluster will perform the local gradient measurements required to identify the causal mechanism for generating auroral arcs. The satellite-based electron beam resolves the most significant outstanding auroral problem by "being at the right place at the right time – and knowing it".

Mars Aeronomy Probe

Mars Aeronomy Probe will determine the direct, dynamic coupling of a dusty atmosphere with the solar wind. It is a single spacecraft that will orbit Mars. Instruments will measure the composition, thermal profile, and circulation in the Martian upper atmosphere. Mars Aeronomy will determine the sources and sinks of ionospheric plasma, its coupling to other regions of the atmosphere, and its to the solar wind.

Particle Acceleration Solar Orbiter (PASO)

PASO will determine how the most energetic particles are accelerated and transported in and around the Sun. It is a single spacecraft that follows active solar regions for extended periods by virtue of the spacecraft's heliosynchronous orbit (from 0.2 to 0.3 AU) in the ecliptic plane. This orbit is achieved through the use of a solar sail. The spacecraft uses a combination of *in situ* and remote sensing instruments to measure the energy spectrum and composition of ions from below 1 MeV to above 100 MeV/nucleon, the neutron energy spectrum above 5 MeV, the Gamma-ray spectrum with sufficient resolution to resolve nuclear lines, and the *in situ* solar wind electrons, ions, and magnetic fields. Key to the mission is the extended measurement of nuclear lines with sufficient resolution to determine particle directionality (by Doppler shift) and track changes in spectral evolution and composition in a solar flare. The energy spectrum and composition of the particles accelerated out of the flare will then be measured directly with the *in situ* instrumentation.

Venus Aeronomy Probe

Venus Aeronomy Probe will study the robust upper atmosphere and solar-wind atmosphere interaction of a planet with essentially no intrinsic magnetic field. This mission will determine the processes by which solar wind energy is transmitted to the ionosphere and upper atmosphere. It will also study how charged particles are accelerated to create auroral-type emissions, how magnetic field ropes form and dissipate, how ionospheric plasma is lost, as well as other electrodynamic interactions.

3.3 Define the origins and societal impacts of variability in the Sun-Earth connection.

Solar variability has significant short-term and long-term impact on society. The Living With A Star program is a long-term effort to determine the physics behind those aspects of the connected Sun-Earth system that directly affect life and society. It advances the understanding of the network of processes that couple the activity-generating processes within the Sun to the responses within geospace, down to the Earth's atmosphere. The magnitude of the problem requires dedicated NASA/LWS missions, comprehensive modeling and data assimilation, as well as intra-agency, inter-agency, and international collaboration. Development of this program requires several phases, where significant progress is already made in the near-term (during the rise of the next solar cycle, or Phase I) using a combination of solar and geospace missions. The solar mission focuses on the physics behind solar variance and its impact on society while the geospace missions focus on the geospace environment causing spacecraft charging, single event upsets, human exposure to radiation, disturbances to radar, communications, and navigation and errors in orbital prediction.

In the intermediate-term, Phase 2, deeper understanding of the complex coupling of the Sun-heliosphere-Earth system is developed, with particular emphasis on the evolution of solar disturbances in the inner heliosphere inside 1 AU and the linking of solar/magnetospheric forcing of the Earth's ionosphere with forcing from the lower atmosphere. Finally, in the long-term, missions prepare for an "operational" mission by investigating the ability to extend forecasting of solar disturbances, completing an understanding of the full, end-to-end links of the Sun-heliosphere-Earth system, and investigating long-term solar variability.

Table 3.3.1 Near-, Intermediate-, and Long-term missions that define the origins and societal impacts of variability in the Sun-Earth connection.

Near-Term Missions (2003 – 2008)	Intermediate-Term Missions (2009-2014)
<p>Solar Dynamics Observatory (SDO)</p> <ul style="list-style-type: none"> - What mechanisms drive the quasi-periodic 11-year cycle of solar activity? - What solar magnetic field configurations lead to CMEs, filament eruptions, and flares and can these events be forecasted? - Where do variations in the Sun’s total and spectral irradiance arise? <p><u>Geospace Storm Probes:</u></p> <ul style="list-style-type: none"> • Ionosphere Thermosphere (IT) Storm Probes <ul style="list-style-type: none"> - What is the contribution of solar EUV to ionospheric variability? - How does the middle- and low-latitude IT system respond to geomagnetic storms? - How do ionospheric storms develop, evolve, and recover? - How are ionospheric irregularities produced? • Radiation Belt Storm Probes <ul style="list-style-type: none"> - Which physical processes produce radiation belt enhancements? - What are the dominant mechanisms for relativistic electron loss? - How does the ring current affect radiation belt dynamics? 	<p>Inner Heliosphere Sentinels</p> <ul style="list-style-type: none"> - How does the global character of the solar wind and energetic particles in the inner heliosphere change with time? - What is the distinction between flare and shock accelerated particles? <p>Solar Orbiter</p> <ul style="list-style-type: none"> - What are the links between the solar corona and the heliosphere? - What is the nature of the inner heliosphere solar wind? <p>Inner Magnetospheric Constellation</p> <ul style="list-style-type: none"> - How do the radiation belts, ring current, and plasmasphere couple to produce changing energetic particle populations? - What is the origin, dynamics, and consequences of day/ night and dawn/dusk asymmetries in the inner magnetosphere? <p>Tropical ITM Coupler</p> <ul style="list-style-type: none"> - How are the mesosphere, thermosphere, ionosphere and plasmasphere coupled? - How does the ionosphere and thermosphere respond to forcing from the lower atmosphere? <p>Magnetic Transition Region Probe (MTRAP)</p> <ul style="list-style-type: none"> - What is the dynamics of the Sun’s magnetic transition region between the photosphere and upper chromosphere? - What processes control the stability of large-scale coronal structures and high density filaments that result in CMEs?
Long-Term Missions (2015 – 2028)	
<p>L1-Diamond</p> <ul style="list-style-type: none"> - How does large-scale turbulence modify the “geoeffectiveness” of solar disturbances? - Can <i>in situ</i> forecasting of solar disturbances be extended to regions closer to the Sun than L1? <p>SIRA</p> <ul style="list-style-type: none"> - What is the global structure of CMEs and other transient and co-rotating regions in the outer corona? <p>Stellar Imager</p> <ul style="list-style-type: none"> - What are the characteristics of stellar activity in stars like the Sun? - What are the signatures of solar activity on time-scales of years to decades? <p>Sun Earth Energy Connector (SEEC)</p> <ul style="list-style-type: none"> - How do solar irradiance variations affect geospace? <p>Sun-Heliosphere-Earth Constellation</p> <ul style="list-style-type: none"> - What are the end-to-end links of solar variability in the Sun-heliosphere-Earth system? 	

Table 3.3.2 Investigations for defining the origins and societal impacts of variability in the Sun-Earth connection and their relation to near- and intermediate-term missions.

Investigation	Near-Term Missions			Intermediate-Term Missions				
	SDO	IT Storm Probes	Radiation Belt Storm Probes	IHS	Solar Orbiter	IMC	Tropical ITM Coupler	MTRAP
(a) Develop the capability to predict solar activity and its consequences in space.	P			S	P			P
(b) Develop an understanding of the evolution of solar disturbances, how they propagate through the heliosphere, and affect the Earth.	S		S	P	S	S		S
(c) Develop the capability to specify and predict changes to the radiation environment.		S	P			P		S
(d) Develop an understanding of the upper atmosphere and ionosphere variability to solar forcing and coupling from the lower atmosphere.		P	S				P	
(e) Understand the connection between solar variability, the Earth's upper atmosphere, and global change.		S					S	
(f) Develop the capability to predict the long-term climate of space.	S	S	S					S

P = Primary science investigation for the mission

S = Secondary science investigation for the mission

3.3.1 Near-Term Missions (Phase I)

The Phase I LWS missions are designed to make significant progress on specific LWS objectives including the origins and consequences of magnetic activity on the Sun, the radial dynamics of the radiation belts, and the formation and evolution of ionospheric irregularities.

Solar Dynamics Observatory (SDO)

SDO will discover the mechanisms that drive solar variations that affect the Earth. It is a single spacecraft that images the Sun from Earth orbit. SDO will be the first mission to view the entire domain of the Sun where magnetic fields originate and cause the variations that affect life and society. Its

two principal functions are to make measurements of solar parameters that are necessary to provide a deeper understanding of the mechanisms that lie at the foundation of the Sun's variability on all time scales, and to provide measurements of the radiative, particulate, and magnetized plasma output of the Sun that affect the terrestrial environment and the heliosphere in which it is embedded. To do this, SDO focuses on the dynamics of the solar magnetic field and of the plasma contained in it. It carries a helioseismic/magnetic imager with high spatial and temporal resolution and continuous full-disk coverage, an Atmospheric Imaging Array, providing full disk imaging at different levels in the solar atmos-

phere, a white light coronagraph, and a spectral irradiance investigation. The spacecraft will be in geosynchronous orbit for nearly continuous solar monitoring and to take advantage of significant downlink capability. Key to the mission is the unprecedented temporal cadence and spatial resolution of the solar imaging. With this imaging, SDO performs helioseismic measurements to assess changes in the structure and dynamics of the solar interior associated with magnetic fields; it images the entire coronal atmosphere at high spatial, temporal, and thermal resolution; it observes the irregularities traveling into the heliosphere; and it measures the spectral irradiance in the EUV. Thus it provides, for the first time, a comprehensive view of the entire magnetic system of the Sun.

Geospace Storm Probes:

• Ionosphere Thermosphere Storm Probes

The IT Storm Probes specify the ionospheric irregularities that affect communications, navigation, and radar systems, by understanding how the variability of Sun and magnetosphere affect the ionospheric electron density and its irregularities. Two spacecraft will fly in middle-inclination orbits around 400 km in altitude, with ascending node separations varying from 2 to 20 degrees. In this orbit, the spacecraft traverse the mid-latitude ionosphere, a critical region for ionospheric irregularities. These spacecraft carry *in situ* instruments to measure, for example, ionospheric density with height, density irregularities, scintillations, plasma drifts (or electric fields), and the density, composition, and bulk displacements (winds) of the neutral particle population. Key to this part of the IT mission is the use of more than one satellite to resolve the spatial extent of ionospheric irregularities and distinguish spatial and temporal variations in these structures. It is desirable to support these two LEO spacecraft with an ionosphere-thermosphere imaging instrument on a geosynchronous platform to measure the global oxygen to nitrogen ratio and electron density. This imager establishes the global response to solar and geomagnetic forcing as well as context information for the in-situ measurements.

• Radiation Belt Storm Probes

The Radiation Belt Storm Probes will determine the processes responsible for dynamic changes in the radiation belts. It is a pair of spacecraft in low-inclination geostationary transfer orbits, with particle and field instruments to carry out comprehen-

sive in-situ measurements of the radiation belts and ring current in the inner magnetosphere. These spacecraft will determine the processes responsible for radiation belt enhancements, the dominant mechanisms for relativistic electron loss, and the role of the ring current. The spacecraft orbits are chosen such that the instruments sample a range of conditions within the radiation belts. Two or more spacecraft are required to resolve temporal and spatial variations, particularly in the direction radially away from the Earth. These spacecraft measure the acceleration and transport processes and investigate the temporal and the radial spatial structure of the electric and magnetic field variations responsible for acceleration of particles. Measurements include the radiation belt particle fluxes at a variety of radial separations, pitch angle distributions, ring current ion composition, and electric and magnetic fields.

Combined LWS missions in the Near-Term

One of the important elements of the LWS program is the study of the Sun-heliosphere-Earth as a system. It is only through study of this highly coupled system that an understanding of the societal impacts on solar variability will be developed. Thus, the LWS missions in Phase I are designed to have overlapping operation within the geospace mission as well as between the geospace and solar missions.

The joint operation of the Ionosphere Thermosphere and the Radiation Belt Storm Probes allows measurement of the interaction between magnetosphere, ionosphere, and thermosphere, including how magnetospheric particle populations and ring-current changes affect the lower-altitude plasmasphere, and how particles from the ionosphere couple to the magnetospheric population.

The joint operation of the Geospace missions and the Solar Dynamics Observatory allows determination of the forcing from the sun on the upper atmosphere. In particular, the irradiance instrument(s) on SDO provide essential, simultaneous measurements of the EUV spectral irradiance that couples directly to the evolution of density and composition of the ionosphere. Similarly, the geospace missions provide context for the study of the solar activity that gives rise to geoeffective events such as drastic changes in the radiation belts during some intense solar storms.

3.3.2 Intermediate-Term Missions (Phase II)

In Phase II, progress is made on additional LWS objectives and links between regions are determined. There are three areas of study that have high priority. The first is the characterization of the inner heliosphere once the evolution of CMEs near the Sun is determined by SDO. The second is the combined radial and longitudinal dynamics of the inner magnetosphere and the links between the radiation belts and the outer magnetosphere once the radial dynamics are determined by the Radiation Belt Storm Probes. The third is the coupling of the ionosphere, thermosphere, and magnetosphere including forcing from the lower atmosphere once the solar forcing of the ionosphere is determined by the Ionosphere Thermosphere Storm Probes. Upon completion of this set of missions, LWS will have attained a minimal systems approach that is needed to study the many couplings and interactions within the entire Sun-Earth system. Four new missions are needed to reach the next phase of implementation of the LWS program:

Inner Heliosphere Sentinels

IHS will determine the initial evolution of geoeffective disturbances. It is a multi-spacecraft mission with four small spacecraft that have *in situ* experiments (including high-energy particle spectrometers) complemented by a single, larger spacecraft that also carries a high-energy imager. These spacecraft fly in 4 different, highly eccentric orbits in the inner heliosphere designed to give good coverage in solar longitude and distance at all times during the mission. These multi-point measurements are used to investigate the structure of the solar wind and embedded magnetic field, the evolution of perturbations as they propagate from the Sun to Earth, and the generation of shocks and associated energetic particles.

Solar Orbiter

Solar Orbiter delineates links between the solar corona and the heliosphere. It is a European Space Agency (ESA), single-spacecraft mission that makes unprecedented observations in heliosynchronous segments at heliocentric distances near 0.2 AU out of the ecliptic plane to heliographic latitudes of $30^\circ - 38^\circ$. It will use a combination of *in situ* particle and field measurements, radio sounding, and visible UV, and EUV imaging. With this instrument complement and a heliosynchronous perspective, Solar Orbiter will investigate the inner work-

ings of the solar dynamo, track the birth and evolution of solar activity, and make the first out of the ecliptic images of CMEs during their creation and early evolution stages. The combined Inner Heliospheric Sentinels and Solar Orbiter missions will provide a powerful tool for determining the global, 3-D structure of the inner heliosphere and the evolution of solar disturbances within it.

Inner Magnetospheric Constellation

IMC will determine the interaction among the radiation belts, outer magnetosphere, and plasmasphere. It is multiple spacecraft in at least two ecliptic plane “petal” orbits. This spacecraft fleet focuses on detailed specification of the orbital environment of most spacecraft and manned missions, to determine in detail the origin and evolution of particle populations and their interaction with the evolving electro-magnetic field during magnetic storms. The in-situ measurements from these multiple positions allow the construction of comprehensive “weather maps” of the inner magnetosphere (1.5-12 Earth radii) that evolve in response to Sun-induced disturbances. These observations extend the radiation belt storm probe results by making simultaneous maps of the radial as well as the longitudinal variations in the radiation belts. Large day/night and dawn/dusk asymmetries exist in the inner magnetosphere and complicate the global specification of particles and fields. Through simultaneous measure of radial and longitudinal variations in the radiation belts, the temporal and spatial asymmetries will be resolved.

Tropical ITM Coupler

Tropical ITM Coupler will determine the lower atmosphere forcing of the ionosphere at low latitudes. It is a multi-spacecraft mission where two spacecraft are in highly elliptical, equatorial orbits that have conjugate apogee and perigee so that one is at 1500 km apogee while the other is at 150-250 km altitude. A third spacecraft is at intermediate, circular low-inclination orbit. The intermediate altitude spacecraft provides remote sensing of the Earth's lower atmosphere, including waves, winds, airglow, and lightning and tropical thunderstorm monitors. The two spacecraft in highly elliptical orbit provide in-situ wind and particle measurements. This mission focuses on the dynamics of neutral and charged particles as they traverse the interfaces between the mesosphere, thermosphere, ionosphere, and inner plasmasphere at low-altitudes

where the magnetic field has a largely horizontal configuration. A better knowledge is needed of the lower atmosphere coupling. Specifically how large-scale neutral winds, gravity waves produced by input from the lower atmosphere, and ion drifts are coupled and vary with solar activity.

Magnetic TRAnsition Region Probe (MTRAP)

MTRAP will discover the processes that control the appearance, transport, and destruction of magnetic fields through the transition region in the solar atmosphere. It is a single spacecraft in geosynchronous Earth orbit. The transition region controls the stability of large-scale coronal structures and is key to understanding the stability and instability of the high-density filaments that result in the most significant CMEs. MTRAP will observe sites of transition region reconnection and the generation and dissipation of high-energy particles. The mission will measure the magnetic field and the associated plasma dynamics in the chromosphere and transition region with unprecedented resolution and cadence that is attainable only from Earth orbit. The observations will consist of visible and infrared maps of vector magnetic fields and velocities in the magnetic transition region between the photosphere and the corona. It will have a large field of view ($>100,000$ km), high resolution (<100 km), and high sensitivity (<30 G in transverse field). At higher levels in the upper chromosphere and lower transition region there will be UV maps of the magnetic field and velocity, including the full vector field if technically feasible. Finally, there will be an EUV imaging spectrograph to observe coronal structures in the field of view, with comparable resolution.

3.3.3 Long-Term Missions (Phase III)

The long-term missions of the LWS program include a multi-spacecraft mission to provide a global view of the Sun, imaging of other solar-like stars, a multi-spacecraft mission to study to multi-scale processes in the inner heliosphere, and multi-spacecraft missions to measure the evolution of small-scale irregularities within the magnetosphere and ITM environment.

L1-Diamond

L1-Diamond will determine the large scale, three-dimensional structure of disturbances that propagate toward the Earth and will determine the

practicality of continuous monitoring solar disturbances from a vantage point closer to the Sun than L1. It builds on the multi-spacecraft measurements from L1 using existing assets. The mission consists of four identically instrumented spacecraft with wide separation (up to 100's of R_E) centered approximately near L1, but with at least one spacecraft closer than L1. Solar sail technology is used to maintain spacecraft separation and keep the spacecraft in non-Keplerian orbits.

Solar Imaging Radio Array (SIRA)

SIRA will determine the global structure of CMEs and other transient and co-rotating structures in the outer corona. It consists of 10-16 identical microsat spacecraft in a quasi-spherical constellation with ~ 100 km diameter in a nearly retrograde orbit $\sim 10^6$ km from the Earth. These spacecraft will carry radio receivers with frequency and time resolution optimized for solar radio burst detection and analysis. This will enable tracking of CMEs from the Sun to 1 AU, thus considerably improving the accuracy of space weather forecasting. In addition, imaging of type III (fast drift) radio bursts will permit the mapping of interplanetary magnetic field topology and density structures in the solar wind.

Stellar Imager

Stellar Imager will determine the long-term variability of the Sun by imaging other solar-like stars. These observations will be used to develop and test a solar dynamo model with predictive capabilities. Developing that dynamo model, and testing it for long-term predictions of solar activity is impractical if only the Sun is used, as it would take centuries to see the Sun go through only a limited part of the possible states of the nonlinear dynamo. SI will image dozens of Sun-like, magnetically active stars with sufficient resolution to see the patterns of field emergence and evolution, revisiting stars frequently over up to a decade to map out the patterns in the dynamo, and to test and validate dynamo models. It will make use of asteroseismic methods to image the internal rotation profiles of stars. The ultimate SI mission is a multi-spacecraft space-based interferometer working in the visible and UV: at least nine meter-class light collectors and a central beam-combining module, with a maximum baseline of up to 250 m, capable of frequent reconfigurations on a time scale of order 10 hours, operating in a very stable part of space, such as the Sun-Earth L2 point outside the Earth's orbit.

A pathfinder mission of two or three free flying spacecraft would be able to study the least active stars (rotating slowly with few active regions) and form a logical successor to the boom-based Space Interferometry Mission. Ideally, the SI would be a multi-directorate mission, as its imaging capabilities are of direct interest to studies of stars in particular and the universe in general.

Sun Earth Energy Connector (SEEC)

The SEEC mission will perform a comprehensive, global imaging of the solar atmosphere and the near-Earth space environment simultaneously. SEEC will determine how solar irradiance variations affect geospace. SEEC instruments sense selected bands of radiation that reveal primary physical processes occurring within the solar atmosphere and Earth's plasmasphere, ionosphere, and neutral atmosphere.

Sun-Heliosphere-Earth Constellation

The Sun-Heliosphere-Earth Constellation mission requirements depend critically on the results of the near- and intermediate-term mission results. This mission uses the knowledge acquired from

these missions to place a constellation of spacecraft in each of the key coupling regions of the Sun-heliosphere-Earth system so that a complete end-to-end understanding of this system is obtained. This constellation provides the knowledge and understanding of the coupled system that is required to field an operational space weather constellation.

3.4 Inter-relationships between SEC missions

The strong coupling between elements of the Sun-heliosphere-Earth system necessitates a similar linkage between missions in the SEC Division. This combination of missions is aided by the evolution from single-point or widely spaced multi-point missions employing largely one measurement technique to coupled, multi-point missions that employ a variety of measurement techniques. As a result, many SEC missions have additional objectives that extend beyond the three primary objectives of the SEC Division. Table 3.4.1 and 3.4.2 list the SEC near and intermediate missions, their primary objectives, and their additional objectives. Missions are listed in approximately time-phased order.

Table 3.4.1 Near-Term missions and their primary and secondary science objectives

Mission /Science Objective	Primary SEC Science Objectives							
	1. Understand the changing flow of energy throughout the Sun, heliosphere, and planetary environments	2. Explore the fundamental physical processes of space plasma systems	3. Define the origins and societal impacts of variability in the Sun-Earth connection	Understand the structure of the universe from its earliest beginnings to its ultimate fate	Learn how galaxies, stars, and planets form, interact, and evolve	Understand the formation and evolution of the solar system and Earth within it	Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system	Chart our destiny in the solar system
Solar B	P	S	S					
Stereo	P		S					S
SDO	S		P	S	S			S
MMS	S	P						
GEC	P		S			S		S
IT Storm Probes	S		P					S
Bepi-Colombo		P			S	S		
RB Storm Probes	S		P		S			S
Solar Probe	P	S	S			S		S

P = Primary science investigation for the mission

S = Secondary science investigation for the mission

Table 3.4.2 Intermediate-Term Missions and their Primary and Secondary Science Objectives

Mission / Science Objective	Primary SEC Science Objectives							
	1. Understand the changing flow of energy throughout the Sun, heliosphere, and planetary environments	2. Explore the fundamental physical processes of space plasma systems	3. Define the origins and societal impacts of variability in the Sun-Earth connection	Understand the structure of the universe from its earliest beginnings to its ultimate fate	Learn how galaxies, stars, and planets form, interact, and evolve	Understand the formation and evolution of the solar system and Earth within it	Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system	Chart our destiny in the solar system
JPO		P			S	S		
Solar Orbiter	S		P					S
IHS	S	S	P					S
IMC	S		P					S
MC	P		S					
Telemachus	P	S	S			S	S	
RAM	S	P	S					
ITM Waves	P		S			S		
Tropical ITM Coupler	S		P					S
MTRAP	S	S	P					S
HIGO	P	S			S		S	S

P = Primary science investigation for the mission

S = Secondary science investigation for the mission

Linking missions leads to higher science return and, in some instances, is necessary to attain a particular objective. This linking can occur because the missions are operating at the same time, or because the successful completion of one mission provides important input to the operation of a future mission. In the SEC mission roadmap, there are important combinations of missions that address more than one science objective. Focusing on the near- and intermediate-term, these mission combinations and synergisms are:

3.4.1 Mission Combinations

Connections with L1 missions:

All SEC science objectives benefit greatly from *in situ* observations of solar wind plasma and magnetic fields at L1. The *in situ* observations are used

to determine arrival times and the internal structure of disturbances observed remotely in the solar atmosphere. They provide an additional vantage point to help determine the extent, evolution, and internal structure of large-scale inner heliospheric phenomena. All ITM and magnetospheric missions require L1 observations of the solar wind input.

Solar and heliospheric mission links:

Solar B, STEREO, and SDO – Deducing 3-D structures from 2-D images poses one of the most difficult problems in solar physics. By the time SDO is launched, the two STEREO spacecraft will be located at maximum separation from the Earth for the nominal science mission, enabling high resolution imaging of the Sun from three vantage points in the ecliptic plane. The combined missions place the Sun in its proper three-dimensional perspective. Solar B will provide a vector magnetic field

“microscope” and x-ray imaging to complement the SDO full-sun images.

IHS, Bepi Colombo, Solar Orbiter, Solar Probe, Telemachus, RAM, and HIGO – An unprecedented fleet of spacecraft will populate the inner heliosphere at all heliographic latitudes from 4 solar radii to beyond 1 AU. Solar Orbiter will co-rotate (at times) with the Sun. Bepi Colombo will provide inner heliosphere observations from its orbit around Mercury. IHS will observe from multiple ecliptic locations, Solar Orbiter from mid latitudes, and Solar Probe and Telemachus will observe all heliographic latitudes in their pole-to-pole scans. RAM will provide very high-resolution images of the solar atmosphere that will be placed in their global 3-D context by the multi-point measurements of individual active regions on the Sun. Finally, the detailed observations of inner heliospheric phenomena provided by this fleet of inner heliospheric missions will aid HIGO in determining their evolution through the outer heliosphere. Taken together, these missions will provide unprecedented coverage of the Sun and inner heliosphere,

Magnetospheric and ionospheric mission links:

MMS, GEC, IT Storm Probes, and Radiation Belt Storm Probes – MMS spacecraft separations will be very small (~10-100 km) at apogee to resolve reconnection regions, but will spread out in other parts of the orbit. These spacecraft will provide a second “petal” orbit for the radiation belt storm probes, providing longitudinal information on radiation belt dynamics. Because the apogee of the MMS orbit will lie beyond geostationary orbit, it will be possible to use MMS and Radiation Belt Storm Probe observations to study of the interaction of the ring current and radiation belts and the inward convection of ring current particle populations. Linking the ionosphere to the magnetosphere is critical to LWS. The addition of GEC high latitude ionospheric observations to those by the IT and Radiation Belt Storm Probes will aid in understanding the creation of ionospheric irregularities at high latitudes, their propagation to mid latitudes, and their implications for magnetosphere-ionosphere coupling.

Magnetospheric Constellation, ITM Waves Coupler, Inner Magnetospheric Constellation, and Tropical ITM Coupler – This fleet of magnetospheric spacecraft will make unprecedented multi-

point measurements of the inner and outer magnetosphere and the intermediate and low latitude ionosphere. With ~ 50 spacecraft in the outer magnetosphere, Magnetospheric Constellation will providing global context of the Earth’s ring current on spatial scales similar to those of state of the art global simulations. This global context will be invaluable to the Inner Magnetospheric Constellation in determining the causes of longitudinal asymmetries in the radiation belts. Similarly, the unprecedented coverage in the magnetosphere and radiation belts will be important in distinguishing effects of solar forcing of the ionosphere, as determined by the magnetospheric missions, from forcing of the ionosphere from below as determined by the ITM Waves Coupler and Tropical ITM Coupler.

System-Wide Mission Links:

Solar B, STEREO, SDO, MMS, IT Storm Probes, and Radiation Belt Storm Probes – This combination of missions provides unprecedented details of the entire Sun-heliosphere-Earth system extending from inside the Sun down to the ionosphere. SDO will provide measurements of the solar interior and the development of solar disturbances, Solar B and STEREO will follow these out into the heliosphere and determine their evolution, MMS will make measurements in the outer magnetosphere that help determine the micro-scale coupling of solar disturbances to the Earth’s magnetosphere, the IT Storm Probes will link the radiation belt and magnetospheric disturbances with the ionosphere, and the Radiation Belt Storm Probes will determine the direct and indirect effects of the magnetospheric response on the radiation belt population. The result will be a system-wide understanding of the physics behind solar disturbances and their geoeffectiveness. In the intermediate-term missions, a similar set of missions will focus on multi-point evolution of the disturbances in the inner heliosphere, their large-scale coupling to the magnetosphere, their global effects on the ring current, and their effects on the upper and lower atmosphere.

3.4.2 Mission Synergisms

Exploring the Sun: Solar B, RAM, MTRAP

Solar exploration follows three logical progressions related to resolution, full disk imaging, and changing vantage points.

The Solar B, RAM, and MTRAP missions provide an example of increased spatial resolution

ranging from 1 arcsec EUV imaging, to ~ 0.001 arcsec imaging. This progression allows understanding of the morphology and dynamics of large-scale features in the solar atmosphere with increasingly finer scales elucidating the underlying mechanisms that create the dynamics. SDO and Solar Orbiter provide a progression of full disk, synoptic science and helioseismology, first from the equatorial plane, and later from higher latitudes.

Exploration of the Heliosphere: STEREO, Solar Probe, Telemachus, IHS, HIGO

The heliospheric mission sequence will study the inner heliosphere and then progress to the outer heliosphere. The initial 3-D imaging of solar disturbances and their evolution in the inner heliosphere toward the Earth will be made by STEREO. Following that mission, the multi-point measurements of the Inner Heliosphere Sentinels, Solar Orbiter and Bepi-Colombo will determine the global evolution of solar disturbances throughout the inner heliosphere. Solar Probe, Telemachus, and Solar Orbiter will describe the evolution of disturbances in the inner heliosphere out of the ecliptic including the solar polar regions. Finally, the Heliospheric Imager and Galactic Observer will image the outer heliosphere in preparation for subsequent *in situ* exploration.

Exploration of the Magnetosphere: MMS, Magnetospheric Constellation, Radiation Belt Storm Probes, Inner Magnetospheric Constellation

Because boundary layer processes occurring on the smallest scales control large-scale dynamics, the MMS mission will focus on microphysical processes at the magnetopause and inside the magnetotail current sheet: magnetic reconnection, charged particle acceleration, and microscale turbulence. It will serve as the plasma physical “microscope,” investigating scales too small to be resolved by

global circulation models. Parameterized results will feed into global magnetospheric models. Magnetospheric Constellation will function as a “meso/macro-scope” for Earth’s magnetosphere. Ultimately, it will also yield a new understanding on the magnetosphere as a complex nonlinear dynamical system by completing the exploration of scale sizes begun by MMS. Similarly, the Radiation Belt Storm Probes will focus on the radial evolution of the belts and their interaction with the mid-latitude ionosphere. Inner Magnetospheric Constellation will extend this knowledge by determining simultaneous radial and azimuthal properties of the radiation belts and their interaction with the outer magnetosphere.

Exploration of the Ionosphere Thermosphere Mesosphere: GEC to IT Storm Probes, ITM Waves, and Tropical ITM Coupler

The ITM mission sequence will determine the response of the upper and lower atmosphere and ionosphere to forcing from above (i.e., the magnetosphere and solar wind), and below (from the lower atmosphere to the upper atmosphere). The GEC mission focuses on forcing from above at high latitudes, where solar and magnetospheric effects are significant. The IT Storm Probes address forcing from above at mid-latitudes, where there are significant societal affects. Subsequent ITM Waves and Tropical ITM Couplers define forcing from below at mid latitudes and at low latitudes. The end result will be the complete specification of atmospheric forcing from above and below over the full range of latitudes.

A timeline of the near- and intermediate-term missions, grouped by program (STP, LWS, and Other), is shown in Fig. 3.2, SEC Near- and Intermediate-Term Mission Timeline.

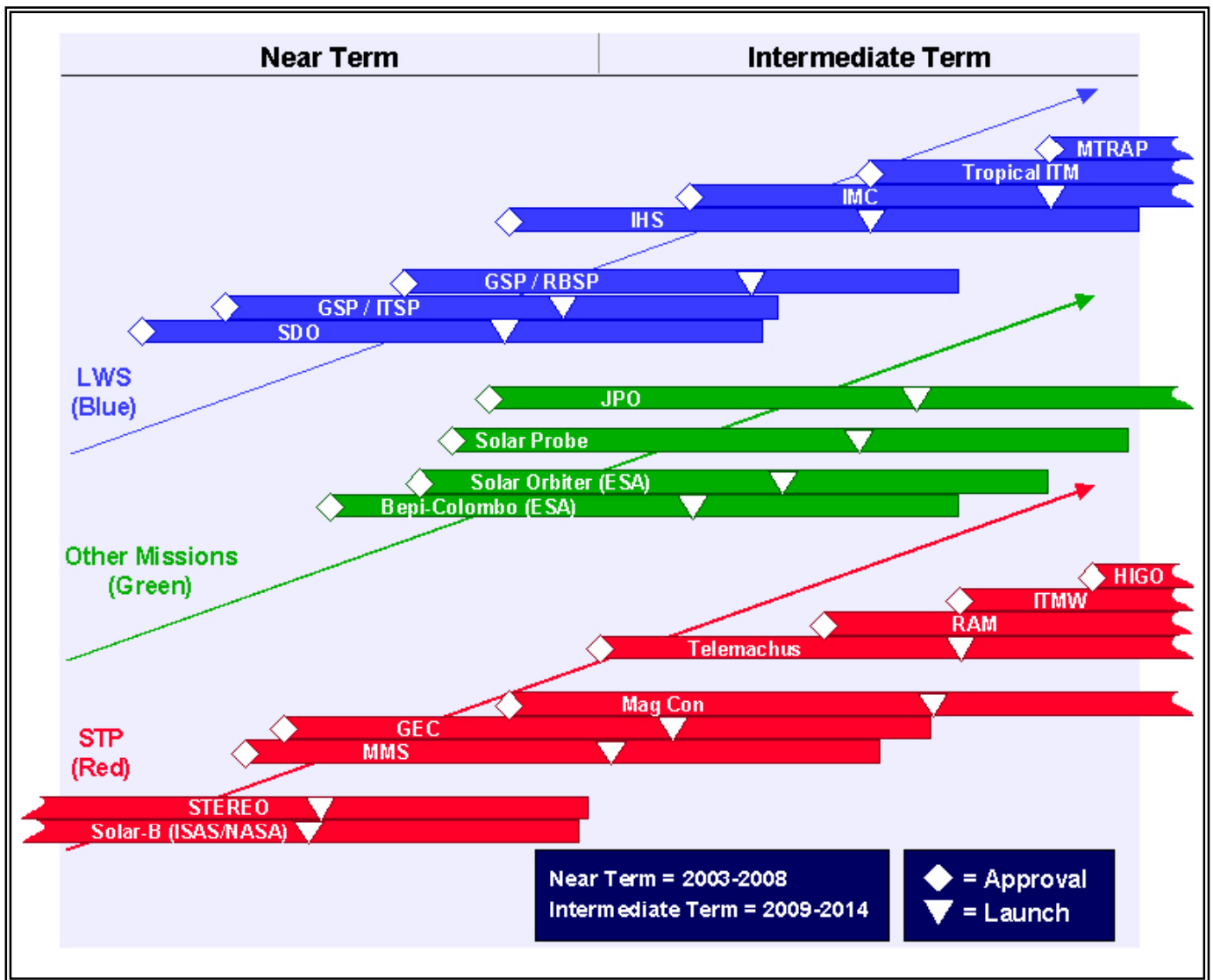


Figure 3.2 SEC Near- and Intermediate-Term Mission Timeline